The galactic 511 keV line and the intergalactic positron density

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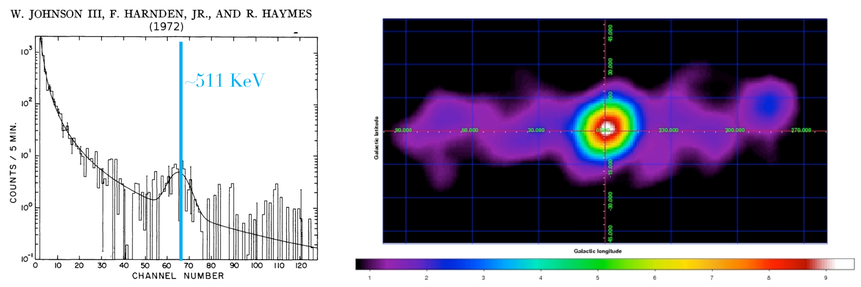
based on A. Vecchio, A.C. Vincent, J. Miralda-Escudé and C. Peña Garay, arXiv:1304.0324

Summary

10^{43} positrons per second annihilate in a compact spherical region around the centre of the Milky Way. At present, known astrophysical sources cannot account for the signal. We propose a novel scenario in which extragalactic positron sources such as radio jets of active galactic nuclei (AGN) fill the intergalactic medium with MeV-scale e^+e^- pairs, which are then accreted into galaxies like the Milky Way. Interpreting the diffuse cosmic radio background (CRB) as arising from synchrotron radiation by such sources suggests that the intergalactic positron-to-electron ratio may be as high as 10^{-6}. Assuming a simple spherical accretion model, this could account for the 511 keV emission of the Galaxy.

The 511 keV sky

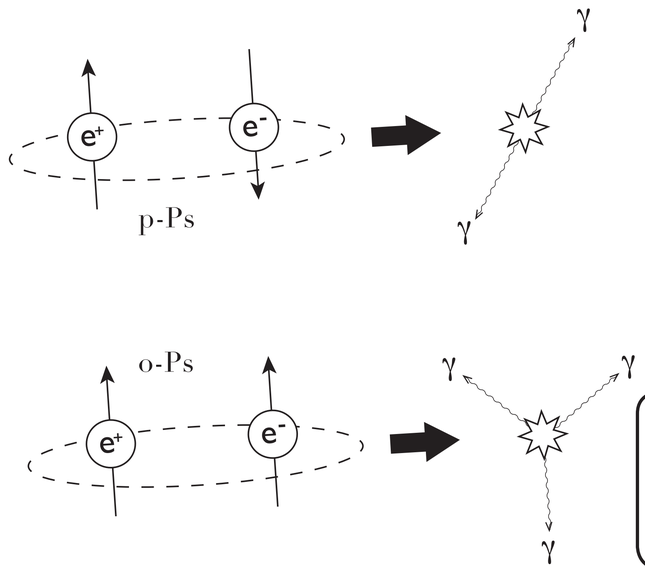
First observed in balloon experiments over 40 years ago, the 511 keV gamma-ray line characterized most recently by INTEGRAL/SPI provides overwhelming evidence of the annihilation of $2 \cdot 10^{43}$ electron-positron pairs per second in a spherical region of a few hundred pc around the galactic centre, and to a lesser extent in the galactic disk. This requires the production of 3 solar masses of positrons over the history of the Galaxy. The observed bulge-to disk (B/D) ratio is ~ 1.4, making conventional galactic e^+ sources unlikely candidates, since they should be correlated with the distribution of stars.

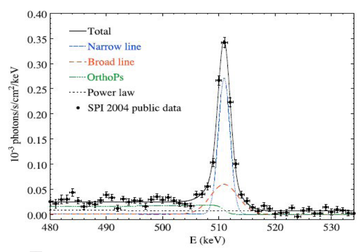


Left: the first observation of the 511 keV signal from the galactic centre (Johnson et al. 1972). Right: the morphology of the signal today, as observed by the INTEGRAL/SPI experiment (Bouchet et al. 2010)

Signatures of positron annihilation

Most commonly, positronium is formed before annihilation of e^+e^- pairs. This occurs in two configurations: the singlet state para-positronium (p-Ps, spin 0) and the triplet state ortho-positronium (o-Ps, spin 1). Conservation of angular momentum ensures that p-Ps decays into two back-to-back 511 keV photons, whereas o-Ps must decay into 3 photons, forming a continuum spectrum.





The gamma-ray spectrum observed by INTEGRAL/SPI clearly shows the p-Ps line and o-Ps continuum, below the line. Various components indicate the composition of the annihilation medium. (Figure above: Jean et al. 2006)

The **observed spectrum** indicates that positrons must be injected at **low energies** into the ISM

The morphology of the 511 keV photon flux in the sky is given by the integral along the line of sight:

$$d\Phi_{511}(\theta,\phi) = 2(1-0.75)\frac{d\Omega}{4\pi}\int_{\text{l.o.s.}} \frac{dN_{e^+e^-}}{dV\,dt}(x,\theta,\phi)dx$$

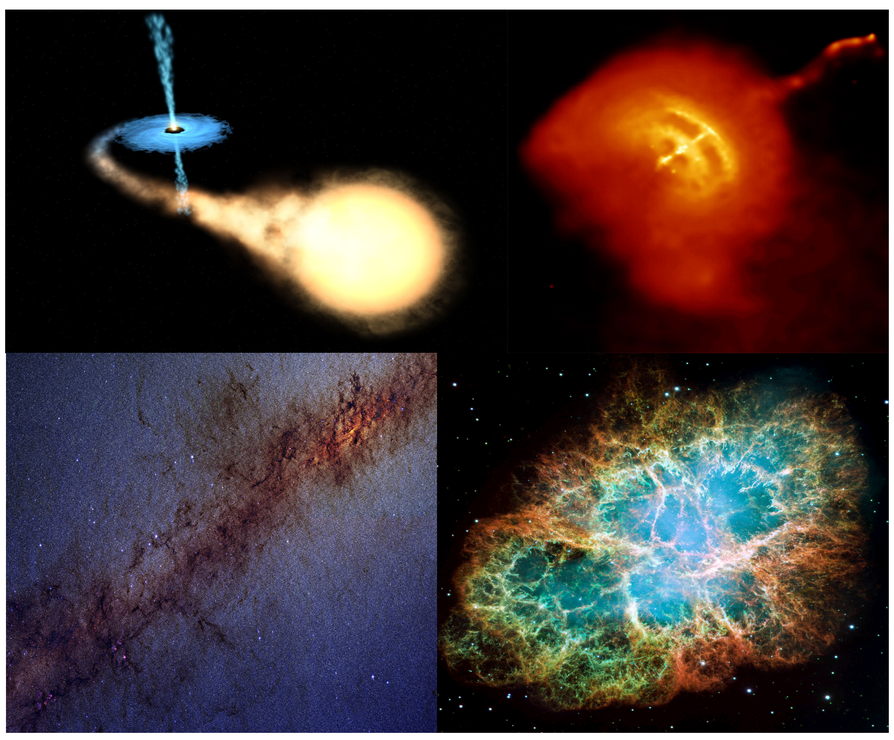
where $dN/dVdt$ is the annihilation rate per unit volume.

Sources of positrons in the Milky Way

Our galaxy contains many sources of antimatter. To properly explain the INTEGRAL/SPI signal, the sources must predict the correct intensity, spectrum and morphology. No known galactic source satisfies all of these criteria:

Source (Requirement)	**Process**	**Intensity** $\sim 10^{43} e^+ s^{-1}$	**Spectrum** $E_{e^+} \lesssim 3$ MeV	**Morphology** B/D $\gtrsim 1.4$
Massive Stars	^{26}Al β^+ decay	✓	✓	×
SNe	^{44}Ti β^+ decay	✓	✓	×
SNIa	^{56}Ni β^+ decay	?	✓	×
Novae	β^+ decay	×	✓	×
Hypernovae/GRBs	^{56}Ni β^+ decay	?	✓	×
Cosmic rays	p–p collisions	?	×	×
Low-mass X-ray Binaries	γ–γ pair creation	✓	✓	×
Microquasars	γ–γ pair creation	✓	✓	×
Pulsars	γ–γ pair creation	✓	×	×
Central black hole	γ–γ pair creation	?	×	✓(?)
Dark Matter*	annihilation	?	✓	✓

*See e.g. Vincent et al. (2012). Table adapted from Prantzos et al. (2011)



Images: (clockwise): microquasar (spacetelescope.org); Vela Pulsar, Crab nebula supernova remnant, and galactic center (wikimedia commons)

arXiv:1304:0324

The intergalactic Positron Density

The cosmic radio background (CRB) is an isotropic component of the radio background in excess of the CMB (Fixsen et al. 2011):

$$T_{\text{radio}} = (1.26 \pm 0.09\text{K})\left(\frac{\nu}{\text{GHz}}\right)^{-2.6\pm0.04}$$

It is consistent with high-redshift synchrotron radiation by electrons or positrons with a power-law distribution of energies:

$$n_e(E)\,dE \propto E^{-p}\,dE$$

If the sources of this radiation are diffusely-distributed, high-energy regions such as the jets and lobes of active galactic nuclei (AGNs, *e.g.* Marscher 1983), then it is possible to compute the number of e^+e^- pairs responsible for the CRB. If a fraction f_I of the positrons escape these environments, we calculate the **average ratio of positrons to electrons in the intergalactic medium**:

$$N_p/\bar{n}_e = 3.6\times10^{-6}\left(\frac{B}{10\,\mu\text{G}}\right)^{-1.6}\frac{10^{7.5}\,\text{yr}}{t_e}\frac{f_I}{\gamma_{min}^{1.2}}$$

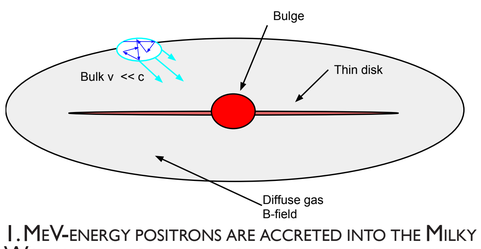
These pairs are naturally produced in the MeV energy range. Given typical values for the lobes of a radio-loud AGN, including a magnetic field of 10 microgauss, a typical escape time t_e of $10^{7.5}$ years (corresponding to the size of the object), this yields:

$$N_p/\bar{n}_e \lesssim 10^{-6} f_I$$

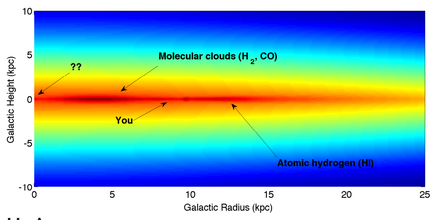
If the majority of the CRB originates instead from jets, this upper limit could be even larger.

Accretion into the Milky Way: the 511 keV signal

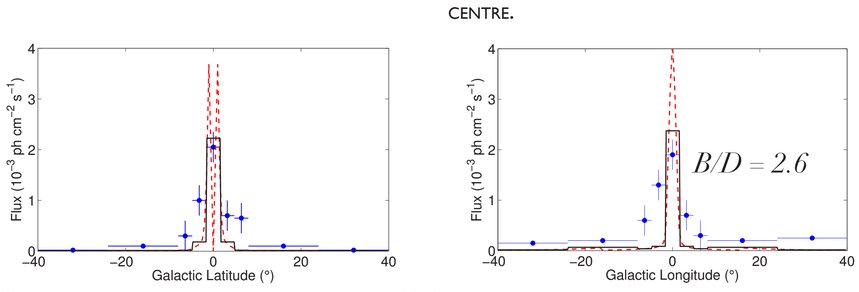
Before annihilating, positrons first thermalize with their medium. However, positrons in the MeV energy range do not efficiently Compton scatter, and can thus live for many Gyr in the intergalactic medium. It follows that, **if they remain magnetically bound** to the plasma in which they escaped their progenitor, they will be accreted into galaxies along with other IGM material.



I. MeV-energy positrons are accreted into the Milky Way within bound structures that travel with a non-relativistic bulk velocity.



II. As the matter is accreted, positrons cool due to interaction with the interstellar gas. There are some uncertainties from the galactic centre.



III. When positrons finally thermalize with the ISM, they rapidly annihilate, giving off an observable 511 keV signal. Red: predicted 511 keV distribution in the sky; black: binned distribution, as would be observed by SPI; Blue: INTEGRAL/SPI data (Bouchet et al. 2010).

References: L. Bouchet et al. (2010) Ap. J. 720 1772; D. Fixsen et al. (2011) Ap. J. 734 5; P. Jean et al. (2006) A&A 445,579; W.N. Johnson et al. (1972), Ap. J 172:L1-L7; A. Marscher (1983) Ap. J. 264, 296; N. Prantzos et al. (2011) Rev. Mod. Phys 83, 1001-1056; Vincent et al. (2012) JCAP 04(2012)022. Support from european contract FP7-PEOPLE-2011-ITN and INVISIBLES, as well as FQRNT.